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THE INTERLEAVED OPERATION OF POWER AMPLIFIERS

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Abstract: Multi-level power stages and control techniques have been developed to increase power-converter operating voltage levels above the voltage ratings of available power-semiconductor switches, and also improve output waveform resolution. The multi-level power-conversion idea, however, may also be adopted more generally in high-power amplifiers. In amplifiers based on the single-phase inverter topology, or H-bridge, this is most easily accomplished by the direct series, or parallel, connection of multiple H-bridge power-stages. Operating these with interleaved PWM control, gives higher output power and produces an improved output voltage spectrum and significantly lower output current-ripple. Consideration is given here to the affect on output waveforms when H-bridge power-stages are series and parallel connected, and controlled by optimally interleaved PWM. Parallel as well as series amplifier connection is shown to produce multilevel output waveforms.

INTRODUCTION

High-bandwidth ($\geq 10\text{kHz}$), high-power ($>10\text{kVA}$) switched-mode amplifiers able to deliver high-slew-rate pulsed and a.c. waveforms of several hundred amps or more are required in magnetic resonance imaging [MRI] [1], electromagnetic geophysical exploration equipment [2], large vibrating table drives, and nuclear and particle physics magnetic stabilisation and beam steering systems [3]. Often, such power amplifiers cannot be implemented without, in effect, parallel or series connecting power devices, or modules, in the output power-stage to give the necessary current and voltage handling capability.

In the case of an MRI systems, for example, three audio-frequency bandwidth power amplifiers are used to drive high-current trapezoidal, burst sinewave, sine pulse or other waveforms for several hundred milliseconds in gradient-field coils. These generate strong orthogonal magnetic fields to decode the spacial distribution of NMR spin signals, the intensity of which is used to map MRI images of body organs. To improve image access time, coil-current di/dt rates of $\geq 0.5\text{A}/\mu\text{s}$ are desirable in coil impedances $\geq (0.5\text{mH} + 0.1\Omega)$. This necessitates more than 250V per 100A voltage-drive capability; and to improve image resolution, very high-

stability, $\leq 50\text{ppm}$, repeatable low-ripple output current waveforms are required which can only be satisfied by switching-amplifier operation above 50kHz. With a single H-bridge power-stage of modern IGBT modules this may seem easily achievable. However, alone, this cannot be operated at a high enough switching-frequency, f_{sw} , to give acceptable output current stability and ripple. High-current power-MOSFET modules are able to operate at f_{sw} between 100 and 500kHz; but modules rated above 300V must be parallel connected in relatively high numbers giving unacceptable cost and reduced f_{sw} capability.

The use of more complex amplifier power-stage circuits has been investigated to overcome these device limitations, such as the series connection and interleaved operation of inverter H-bridges [2,3], the parallel connection and interleaved operation of high-voltage inverter bridge-legs [1], and a single-phase version of the three-phase multi-level inverter circuit [3]. Figs. 1, 10, and 4, respectively, show these options. In effect, all comprise multi-level power-converter topologies.

With series connection, two additional V_s magnitude levels per H-stage may be added to the composite output, V_o (i.e. V_{AD} in Fig.1), shown in Fig.2 (NB $V_s=100\text{V}$ used). With parallel connection of n stages, as in Fig.5, two additional levels per H-stage of about V_s/n (if $L_p/L_o \ll 1$) are introduced into the L_o - R_o voltage, shown as V_o in Fig.6. Note, that with parallel connection, additional levels are introduced under the original $\pm V_s$ output-voltage limits (NB $V_s=200\text{V}$ used to give same output current as the series connected example).

Therefore, where a number of parallel, series, or series-parallel connected stages are used to increase amplifier output V_A , provided the stages are well matched, the potential exists to interleave their switching and scale the waveform resolution, or output ripple frequency, in proportion to the stage number. For example, by using an interleaved fixed-frequency, unipolar-voltage-switching strategy to control the individual power-stages, n parallel-connected layers of m series-connected amplifiers shown in Fig.8b gives a $2mn+1$ -level output-voltage waveform with a fundamental ripple-frequency of $2mnf_{sw}$. The load waveforms for a 2x2 system are given in Fig.9: V_o has 9 levels and f_{sw} . $EFFECTIVE = 8f_{sw}$; 8 times the power semiconductor f_{sw} .

SERIES AMPLIFIER CONNECTION

The direct series connection of a number of amplifiers may be used if individual amplifiers have isolated d.c. supplies, as depicted in Fig.1. In this way, the voltage sharing precautions necessary with direct series device connection, or even with the multi-level topology in Fig.4, are avoided since the maximum working voltage of each device is limited to V_S . Using a separate power-supply transformer per stage also gives good connection and maintenance flexibility: faulty stages may be swapped and repaired and amplifiers may be formed and expanded by both the series and parallel connection of the amplifier module.

The composite amplifier gives output voltages that exceed the device voltage-ratings. With m stages, a peak output voltage of approximately $m V_S$ is available. Since no special voltage sharing measures are required; power device, utilisation, switching performance and power conversion efficiency within the composite amplifier are all unaffected.

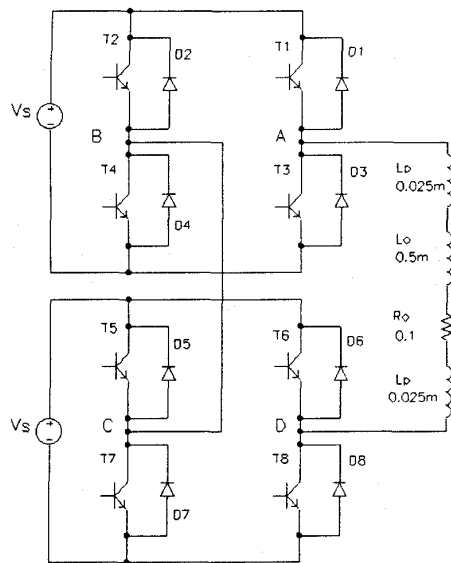


Fig.1 Series-connected H-bridge stages.

The controllers of series-connected H-bridges must share the same current control-loop error signal, and should have appropriately phase-shifted fixed-frequency PWM modulators (i.e. with π/m displaced carrier waveforms at f_{sw}), to give multiple level output-voltage waveforms which minimise output current ripple. For an m -stage amplifier, $(2m+1)$ -level voltage waveforms may be produced; and, provided the amplifier switching and conduction characteristics are well matched, maximum current-ripple amplitude and frequency are improved by factors of $1/m$ and m , respectively. Simulated waveforms for a 2-stage amplifier with a 0.5mH, 0.1Ω load are given in Fig.2 for optimally

phase-shifted PWM control with the modulation index set at 0.8. L_p inductors are added to represent the net effect of second-order output-filter inductance associated with each amplifier. In practice, these may be split within each amplifier to provide balanced outputs, or equal over-current limiting for each half-bridge: the composite output voltage waveform is in principle unaffected. A resistance of $5\text{m}\Omega/L_p$ (not shown) is used to produce Figs. 2 and 3.

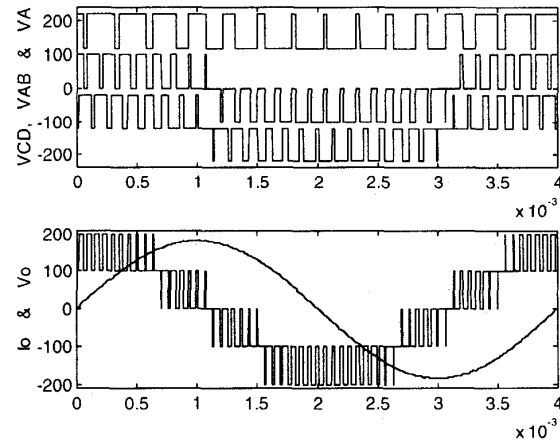


Fig.2 Waveforms for series-connected stages (V_{CD} and V_A are offset by -120V and 120V)

The 5-level V_A - V_D waveform, plotted as V_O in Fig.2, has an effective PWM carrier-frequency of 4 times individual power-device f_{sw} . H-bridge output voltages, V_{AB} and V_{CD} , and half-bridge A voltage, V_A , are given to show how V_{AD} originates.

Current-ripple amplitude is most easily determined by subtracting the fundamental output voltage, V_{O1} , from the output PWM waveform, V_O (see Fig.3), and applying this to the load [4].

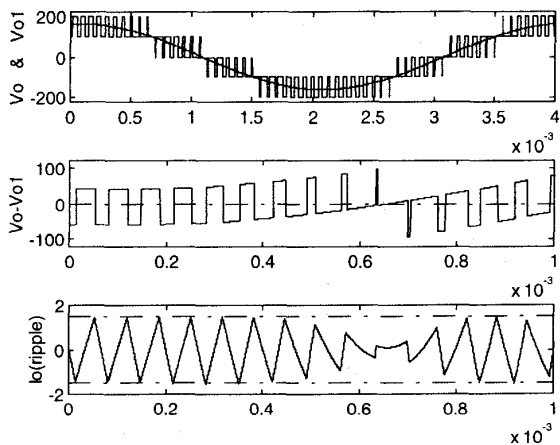


Fig.3 Output ripple for series-connected stages

The maximum peak-to-peak load-current ripple, $\Delta I_{O(max)}$, is approximately given by Eq.1, provided the effective load time-constant is well above $1/f_{SW}$. Calculated $\pm \Delta I_{O(max)}/2$ levels (i.e. $\pm 1.515A$) for $V_S=100V$, $f_{SW}=15f_O$, $L_O+2L_P=0.55mH$, and $m=2$ are overlaid on the ΔI_O waveform in Fig.3. The ΔI_O waveform approaches $\pm \Delta I_{O(max)}/2$ each time the output-voltage-ripple waveform, V_O-V_{O1} , approximates to a squarewave, i.e. $4m$ times per baseband period.

$$\Delta I_{O(max)} = \frac{V_S/2}{(L_O + 2L_P)} \frac{1}{2} \frac{1}{2mf_{SW}} = \frac{V_S}{(L_O + 2L_P)} \frac{1}{8mf_{SW}} \quad 1$$

MULTI-LEVEL INVERTER CIRCUIT

There are several forms of multi-level inverter bridge-leg which have previously been investigated for application in high-voltage 3-phase a.c. machine drives. While this topology also allows higher output-voltages than the individual device voltage-rating to be controlled, it does have significant disadvantages which are mostly enumerated in [3]:

- 9 switching configurations as opposed to 16 for series-connected amplifiers complicate control,
- difficult to design and extend the number of output levels and the maximum output voltage,
- much higher smoothing capacitor volume required,
- 2 more power diodes per basic H-bridge required.

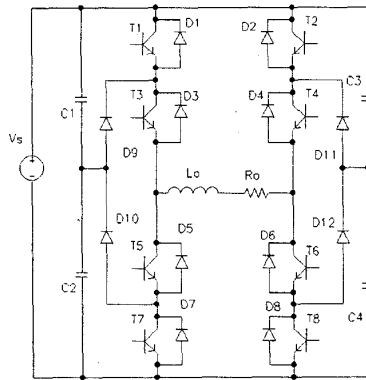


Fig.4 Multi-level single-phase amplifier stage

These disadvantages, together with the additional measures required to ensure smoothing capacitor and power device voltage sharing under all operating conditions, precludes this type of multi-level topology from use in most single-phase amplifier applications.

PARALLEL AMPLIFIER CONNECTION

The parallel connection of H-bridge stages may be made as shown in Figs. 5a, 5b or 10, depending on

whether stages are to be operated from one d.c. supply or are available as modular isolated units. This primarily allows output current-handling capability to be controlled by the number of stages, n . The relative phasing of the PWM carrier waveforms within amplifier modulators is similar to that required for the interleaved series-connected amplifiers.

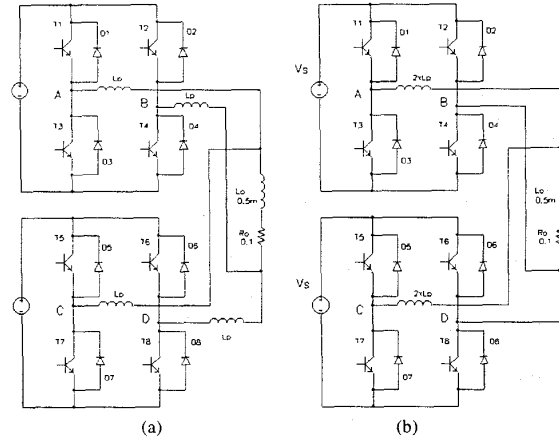


Fig.5 Parallel-connected stages with isolated supplies.

Parallel-connected-amplifier waveforms may be interleaved to the same extent as series-connected ones and produce the same number of levels (i.e. $2n+1$) in the output voltage waveform (c.f. V_O in Figs. 2 and 6). However, it will be shown that from a device utilisation standpoint it is better to work with isolated amplifier modules rather than use a single concentrated power-supply, as in Fig.10, because device current-ripple is considerably lower and has a more favourable spectral content (c.f. I_{P1} and I_{P2} in Figs 6 and 11).

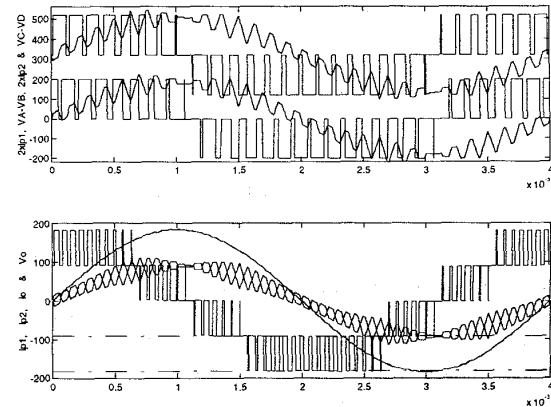


Fig.6 Output waveforms for parallel-connected amplifiers (V_{CD} and $2xI_{P2}$ are offset by 320V and 320A).

The load waveforms in Figs 5a and 5b are the same for equivalent operating conditions. Fig.5b gives the same output as Fig.5a because, with isolated supplies, I_A and I_C must return via points B and D, respectively. Hence

L_{PA} and L_{PB} , and L_{PC} and L_{PD} effectively conduct in series pairs, as shown in Fig.5b. Circuit operation is more easily analysed and simulated using Fig.5b, and more easily used, e.g. as in Fig.8, to show how larger arrays of amplifier modules may be connected.

Simulated waveforms for the Fig.5 connection are given in Fig.6 and the isolated voltage- and current-ripple components are simulated and given in Fig.7 for comparison with Fig.3. With 200V supplies and $L_P=0.05\text{mH}$ ($+0.01\Omega$), the parallel connection gives the same load current and voltage as the series connection with 100V supplies (NB in Fig.2, V_O is taken as V_{AD} rather than across L_O+R_O). The number of voltage levels is similarly determined by $2n+1$, and once again, the maximum output current ripple amplitude and frequency are scaled by $1/n$ and $2nf_{SW}$, respectively. With parallel-connected amplifiers the increased number of voltage levels is produced within $\pm V_S$ limits.

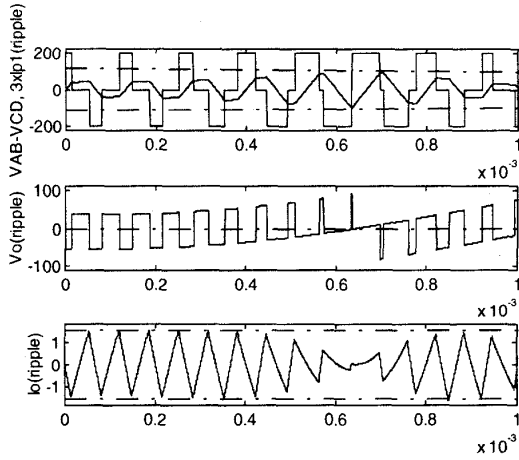


Fig.7 Ripple components for parallel-connected amplifiers.

Whether parallel H-bridge operation is implemented as shown in Figs. 5 or 10, a small value of inductance must be added in series with each amplifier output (or bridge-leg if split, see Fig.5a) prior to parallel connection, and these may also double as the inductors of the second-order output filters of amplifier-modules.

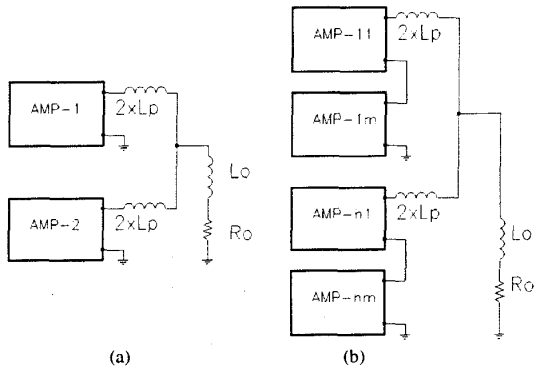


Fig.8 Effective connection of 2 and $n \times m$ multiple stages.

L_P inductors serve to limit the current that effectively circulates between bridge-legs. For a proportion of the PWM switching period when interleaved half-bridges effectively in parallel are in opposite switching states, strings of L_P inductors without the output impedance in series, are directly connected across V_S . Since a small L_P value is desirable to maximise the peak baseband output voltage and for low amplifier volume, the rate of change of current in L_P loops during these shunt connection periods is high and gives a high value of ripple in individual L_P inductors, as seen from I_{P1} and I_{P2} in Fig.6. Although the ripple is interleaved and cancels in the load, it would significantly reduce device utilisation if it were not minimised. By optimising the interleaved switching of all the bridge-legs, the maximum period of shunt L_P connection can be reduced to $1/2nf_{SW}$, as may be inferred from the $V_{AB}-V_{CD}$ waveform in Fig.7.

It is now evident that with parallel connection increased device current-ripple results; whereas with series connection there was no apparent device utilisation penalty. However, provided full use is made of interleaved-switching, the degree of module derating required may be quite small. Maximum device or L_P current ripple $\Delta I_{P(max)}$ can be approximated, using the $V_{AB}-V_{CD}$ waveform in Fig.7 and the simplified L_P and load circuit in Fig.5b. If load time-constants far exceeds $1/f_{SW}$, V_S is effectively applied across $(2L_P+2L_P/L_O)$ for $1/2nf_{SW}$. More generally for n stages

$$\Delta I_{P(max)} = \frac{V_S}{2L_P + \frac{2L_P}{n-1} // L_O} \frac{1}{2nf_{SW}} \approx \frac{(n-1)V_S}{4L_P n^2 f_{SW}} \quad 2$$

If $L_P/L_O < 0.1$, $\Delta I_{P(max)}$ may be further simplified as shown in Eq.2. $\Delta I_{P(max)}$ is approximately inversely proportional to n^2 and falls rapidly as the number of parallel-connected stages increases. Calculated $\pm \Delta I_{P(max)}/2$ levels (i.e. $\pm 36.36\text{A}$) for $n=2$, $V_S=200\text{V}$, $L_P=0.05\mu\text{H}$, $L_O=0.5\text{mH}$, and $f_{SW}=15f_O$ are overlaid on the ΔI_P component of I_P extracted and plotted in Fig.7(top)

It is desirable to minimise L_P value because it reduces the peak amplifier output voltage, although this improves with higher numbers of parallel-connected stages. The output voltage levels, V_{O_i} for an n -stage amplifier are given by Eq.3a, and the effect of L_P on the denominator decreases with increasing n . The difference between voltage levels is given by Eq.3b which tends towards V_S/n for high stage numbers or $L_P/L_O < 0.1$. Calculated $\pm V_{O2}$ and $\pm V_{O1}$ levels (i.e. $\pm 181.8\text{V}$ and $\pm 90.91\text{V}$) for the 2-stage parallel-connected Fig.5 system are overlaid on the V_O waveform in Fig.6.

$$\pm V_{O_i} = \frac{L_O}{\frac{2}{n} L_P + L_O} \frac{i}{n} V_S \quad 3a$$

where $i = 0, 1, \dots, n$.

$$\Delta V_{OL} = \frac{L_O}{2} \frac{V_S}{L_P + L_O} \frac{1}{n} \quad 3b$$

In selecting L_P value, a trade-off has to be made between $\pm V_{OL}$ and $\Delta I_{P(max)}$.

Peak-to-peak load current ripple for 2 parallel-connected stages, $\Delta I_{O(max)}$, is approximately given by Eq.4a. This is used to calculate the maximum ripple for operation with $n=2$, $V_S=200V$, $L_P=0.05\mu H$, $L_O=0.5mH$, and $f_{SW}=15f_O$ as $\pm \Delta I_{P(max)}/2 = \pm 1.515A$. These levels are overlaid on the computed ripple component of output current shown in Fig.7 (bottom).

$$\Delta I_{O(max)} = \frac{\Delta V_{OL}/2}{L_O} \frac{1}{2} \frac{1}{2nf_{SW}} = \frac{V_S}{\left(\frac{2}{n}L_P + L_O\right)} \frac{1}{8n^2f_{SW}} \quad 4a$$

$$\Delta I_{O(max)} \approx \frac{V_S}{L_O} \frac{1}{8n^2f_{SW}} \quad \text{if } n \text{ is high or } L_P/L_O < 0.1 \quad 4b$$

By parallel connecting series strings of amplifier modules whose switching is optimally interleaved, it is possible to further improve output waveform resolution or ripple frequency. The output waveforms and isolated output ripple components for the 2x2 array of amplifier modules (i.e. Fig.8b with $m=2$, $n=2$) is plotted in Fig.9.

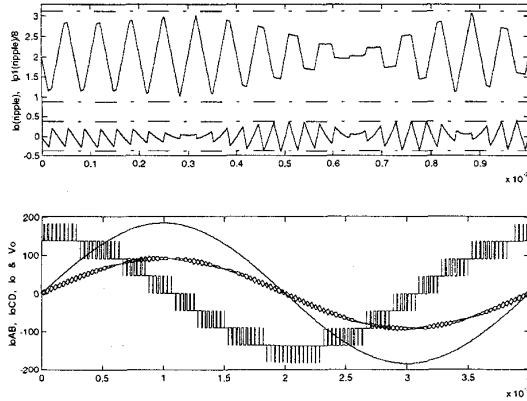


Fig.9 Ripple & output for parallel series-connected stages ($I_P/8$ ripple is offset by 2A and divided by 8).

Output current ripple levels may be approximated by including the number of series connected amplifiers, m , in Eqs 2 and 4 as shown in Eqs. 5 and 7.

$$\Delta I_{O(max)} = \frac{\Delta V_{OL}/2m}{L_O} \frac{1}{2} \frac{1}{2mnf_{SW}} = \frac{V_S}{\left(\frac{2}{n}L_P + L_O\right)} \frac{1}{8m^2n^2f_{SW}} \quad 5$$

If n is high or $L_P/L_O < 0.1$, $\Delta I_{O(max)}$ may be simplified to

$$\Delta I_{O(max)} \approx \frac{V_S}{L_O} \frac{1}{8n^2m^2f_{SW}} \quad 6$$

As seen by the $\Delta I_{P(max)}$ ripple in Fig.9(top), the level of device or I_P current ripple is also reduced in $m \times n$ amplifier arrays. An m^2 factor is included in Eq.2 as shown in Eq.7a. This may be approximated by Eq.7.

$$\Delta I_{P(max)} = \frac{V_S/m}{2L_P + \frac{2L_P}{n-1} // L_O} \frac{1}{2mnf_{SW}} \approx \frac{(n-1)V_S}{4L_Pm^2n^2f_{SW}} \quad 7$$

Eqs. 6 and 7 give $\Delta I_{O(max)}$ and $\Delta I_{P(max)}$ values of 0.758A and 18.18A, respectively; and $\pm \Delta I_{O(max)}/2$ (i.e. $\pm 0.379A$) and $\pm \Delta I_{P(max)}/2$ (i.e. $\pm 9.091A$) levels are overlaid on the appropriate ripple waveforms at the top of Fig.9.

PARALLEL AMPLIFIER CONNECTION WITH COMMON DC SUPPLY

Using a concentrated supply for all parallel-connected stages, as proposed in [4] and shown for a 2-stage system in Fig.10, does allow the same level of waveform interleaving (i.e. also gives $2n+1$ levels in the output waveform). However for the same L_P value, substantially higher levels of current ripple are produced in each of the half-bridges as shown by the simulated I_P waveforms in Fig.11. This arises because current now effectively circulates around $2L_P$ loops rather than $4L_P$ loops as previously, and the driving voltage is no longer $V_{AC}-V_D$ but V_{AC} and V_{BD} .

Given the high level of ripple in I_P waveforms in the Fig.10 system, it is more sensible to be less ambitious with interleaving for this connection and use it to produce $n+1$, rather than $2n+1$, level waveforms, as shown in Fig.12

Output current ripple is increased by a factor of 4 for $n+1$ level operation as seen by comparing Eqs.5 and 8. Eq.8 applies for the Fig.10 circuit and gives $\Delta I_{O(max)}=12.12A$ for the Fig.12 example.

$$\Delta I_{O(max)} = \frac{\Delta V_{OL}/2}{L_O} \frac{1}{2} \frac{1}{nf_{SW}} = \frac{V_S}{\left(\frac{2}{n}L_P + L_O\right)} \frac{1}{2n^2f_{SW}} \quad 8$$

To maintain $\Delta I_{P(max)}$ at a similar level as in the isolated amplifier case the L_P inductor values must be increased by a factor of 4. This is inferred by comparing Eq.9 (if $L_P/L_O < 0.1$ then $\Delta I_{P(max)}$ may be simplified as shown), derived for the unisolated parallel amplifiers, with Eq.2 for the isolated parallel amplifier connection. If $L_P/L_O < 0.1$ then $\Delta I_{P(max)}$ may be further simplified.

$$\Delta I_{P(max)} = \frac{V_s}{L_p + \frac{L_p}{n-1} // L_o} \frac{1}{nf_{sw}} \approx \frac{(n-1)V_s}{L_p n^2 f_{sw}} \quad 9$$

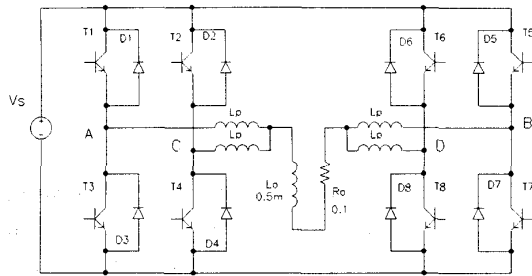


Fig.10 Parallel-connected stages with common supply.

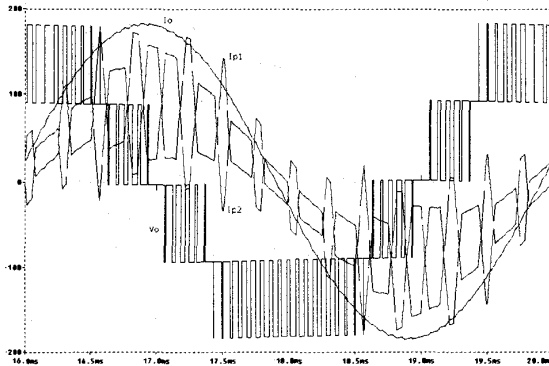


Fig.11 Output waveforms for Fig.10 under same operating conditions as the isolated parallel stages which gave Fig.6.

Simulated waveforms are given in Fig.12 for the system in Fig.10 with operating condition as before, apart from L_p which is here 0.2mH, four times the previously used value. Eq.9a gives 77.78A for $\Delta I_{P(max)}$. Peak output levels are reduced over previous systems because of the higher volt drop now across L_p inductors.

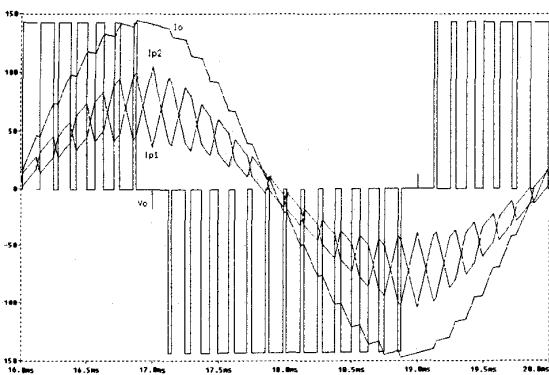


Fig.12 Output waveforms for Fig.10 with reduced interleaving but with the same L_p value.

Using a common power-supply for all parallel-connected stages, therefore, considerably affects peak output voltage and device and output current-ripple for

a given device switching frequency, and the modular system advantages are lost

CONCLUSION

The interleaved operation of series connected amplifiers to give multi-level reduced-ripple output waveforms is quite well understood. It is not so well appreciated that interleaved operation of parallel connected power amplifiers may be used to produce the same effect, and that to get the best output ripple multiplication individual amplifier modules must be supplied from isolated power supplies. Also, where amplifier output capacity is increased by both the series and parallel connection of isolated switching, and artificially multiplying output-ripple frequency without increasing power-semiconductor device switching-frequency, is even greater. Such interleaved PWM control improves output-voltage waveform resolution, and potentially offers improved response over that of single stage amplifiers if output filtering can be relaxed.

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